Characterization of Recoverable Resources from Methane Hydrate Deposits

Year-End Report

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NOTE: *FY2009 FWP covers activity from 11/1/2008 through 12/31/2009*

Task Progress

Task 1: Code Maintenance, Update and Support

Subtask 1.1: Updates, corrections and improvements of the forward hydrate simulation codes

This subtask has been completed. Significant improvements have been implemented into (a) the serial TOUGH+HYDRATE (T+H) code, (b) the parallel TOUGH+HYDRATE (pT+H) code, (c) the coupled T+H/FLAC3D code, which allows the concurrent study of geomechanical processes, fluid and heat flow and thermodynamic states in a hydrate system undergoing changes, and (d) the coupled T+H/G code, for the concurrent study of changes in a hydrate accumulation (usually associated with dissociation-supported gas production) and the corresponding geophysical signature. The T+H Version 1.1 and the corresponding User's Manual were released in August 2009. Several licenses of T+H V1.1 have been granted to various international research organizations. The T+H V.1 has now been fully incorporated into the most recent versions (V1.1) of the coupled T+H/FLAC3D and T+H/G codes, which are being used in several investigations.

Similarly, the pT+H V1.1 code was released in February 2009, and is now the main version of the code used on any multi-processor platform. The code was shared with NETL (2 cost-free licenses), and was purchased by two major international oil and gas companies.

Additionally, several new web-based applications have been developed to significantly improve (a) the creation and modification of input files (*http://esdtools.lbl.gov/input/*), (b) the design and development of complex grids for T+H and pT+H applications (*http://esdtools.lbl.gov/mesh/*), and (c) the ability to predict the properties of hydrate-forming real gas properties (*http://esdtools.lbl.gov/gaseos/*). WebGasEOS, in 2009, was used over 3,600 times by 744 unique visitors from 60 countries. These applications are currently operational, although continuous upgrades are in progress to provide the widest possible range of options and compatibility with new and old formats. In addition, a new advanced, web-based, graphical grid generation tool, based on the LBNL/Yucca Mountain AMESH structured/unstructured grid generating routines and the GMT graphics package, is under development. An alpha release of this

new tool will be placed online for testing in January 2010. New web server hardware has been procured by LBNL, and after professional configuration and testing, the entire ESDTools website will be moved to the newer, faster hardware (while maintaining the same web location).

Subtask 1.2: Improvement of the history-matching parallel I-pT+H code

This task was completed in December 2009. The updated is substantially faster than its earlier version, and its validation process (using laboratory experimental data and data from the Mount Elbert MDT field test) yielded essentially the same parameter estimates. However, a more accurate measure of the code performance can only be obtained after analyzing data from well-monitored (and fully documented) field studies.

Task 2: Support of DOE's Field Activities and Collaborations

Subtask 2.1: Evaluation of production potential and design support for a field test at two potential sites on North Slope, Alaska

Work on this task (which task describes LBNL's participation in a DOE-supported field test under consideration) was completed ahead of schedule. The test under consideration will involve long-term gas production from a Class 3 permafrost hydrate deposit. Under consideration are (a) the Unit D deposit at the Mount Elbert site and (b) the Unit C deposit at the site of the PBU-L106 well, both in North Slope, Alaska. Most of the numerical studies in this task have been completed, and several papers have either been completed or are being prepared.

LBNL staff have completed an analysis of the gas production potential from the Unit D hydrate deposit (a Class 3 system) at the Mount Elbert site, leading to the following publications:

(1) ***Gas Production From a Cold, Stratigraphically Bounded Hydrate Deposit at the Mount Elbert Site, North Slope, Alaska***, by G.J. Moridis, S. Silpngarmlet, M.T. Reagan, T. Collett, and K. Zhang, accepted for publication in the *Journal of Marine and Petroleum Geology.*

This analysis indicates that horizontal wells are clearly preferable to vertical wells for production from such a cold, permafrost-associated deposit. Initial deposit temperature and hydrate saturation are the most critical parameters in determining productivity.

A second related study, involved the use of both random and geostatistical heterogeneous initial conditions and reservoir properties has been completed. The effect of deposit heterogeneity, particularly heterogeneity in initial hydrate saturation, results in dramatic differences in the productivity of the system. "Layered" systems (systems with heterogeneity in the vertical cross-section) show marked improvements in productivity compared to homogeneous initial conditions, while 2-D heterogeneity (either random or geostatistically generated) impede productivity due to the development of persistent, complex secondary hydrate barriers during production. The results will be reported in the following paper under preparation:

(2) ***Effect of Heterogeneity on Gas Production From the Unit D Class 3 Hydrate Deposit at the Mount Elbert Site, North Slope, Alaska***, by M.T. Reagan, G.J. Moridis, and K. Zhang, to be submitted for publication to either *Transport in Porous Media* or to *Journal of Petroleum Science and Engineering*

Additionally, a study of gas production from the warmer Unit C at the site PBU L106 has been completed. This investigation involves very high-definition grids (involving up to 250,000 cells), and seeks to determine not only the gas production potential, but also potential interference with other wells in the vicinity. The results of the study are being included in the following paper under preparation:

(3) ***Design of a potential long-term test of gas production from a hydrate deposit at the PBU-L106 site in North Slope, Alaska: Production predictions and sensitivity analysis***, by G.J. Moridis, M.T. Reagan, T. Collett, K. Boyle and K. Zhang, to be submitted for publication to the *Journal of Petroleum Science and Engineering*

A poster on this subject was presented at the 2009 Fall Meeting of the American Geophysical Union (14-18 December 2009). The results suggest that the long-term test is technically feasible, despite low expected production rates (caused by the relatively low temperature at the site). Use of horizontal well technology could increase these rates by orders of magnitude.

A joint study with NETL (Eugene Myshakin) that aims to investigate the effect of heterogeneity on production from the Unit C deposit at the PBU-L106 site in North Slope, Alaska, is the only one that is still in progress. It is expected that the simulations will be completed in late January 2010, and a joint LBNL-NETL paper will be prepared and submitted for publication to an appropriate peer-reviewed journal.

Subtask 2.2: Geomechanical system response and stability analysis during the proposed production test from the Mount Elbert deposit

This task (which describes LBNL's participation in the DOE-supported field test under consideration that has been discussed previously) was completed ahead of schedule. Two studies that proceed in tandem with the activities in Subtask 2.1 have been completed, and the results are being analyzed. In the first, LBNL staff have completed an analysis of the expected geomechanical response during production from the Unit D hydrate deposit (a Class 3 system) at the Mount Elbert site, and the following paper is in the final stages of preparation:

(4) ***Geomechanical Response and Stability Analysis During Production From a Cold, Stratigraphically Bounded Hydrate Deposit at the Mount Elbert Site, North Slope, Alaska***, by L. Chiaramonte, J. Rutqvist, G.J. Moridis, and T. Collett, to be submitted for publication to the *Journal of Petroleum Science and Engineering.*

In the second study, the simulations of the geomechanical system response during gas production from the Unit C deposit at the site PBU L106 have been completed. The results of the study are being analyzed, and the following paper is in preparation:

(5) Design of a potential long-term test of gas production from a hydrate deposit at the PBU-L106 site in North Slope, Alaska: Geomechanical response and stability analysis, by L. Chiaramonte, J. Rutqvist, G.J. Moridis, and T. Collett, to be submitted for publication to an appropriate peer-reviewed journal.

The most important conclusion of these two studies is that there is practically no surface subsidence and very limited risk of formation and/or well failure during a long-term field test at the two sites because of the stiffness of the overlying permafrost, and because of the limited production rates that can be attained from these cold hydrate deposits.

A paper on the subject of the geomechanical study on the PBU-L106 site was presented at the 2009 Fall Meeting of the American Geophysical Union (14-18 December 2009). The results suggest that the long-term test will result in (a) negligible subsidence at the surface (< 5 mm) because of the stabilizing effects of the stiff permafrost, and (b) no negative consequences for conventional wells operating in the vicinity. Additionally, localized displacements are < 5 cm in the immediate vicinity of the well, and yielding and failure of the formation and/or the well are practically impossible because of the mechanical properties of the hydrate-bearing formation at the site, and because the relatively low production rates prevents a substantial pressure reduction over a wide area.

Subtask 2.3: Feasibility of using geophysical surveys to monitor the proposed production test from the Mount Elbert deposit

This task (completed on schedule) describes LBNL's participation in the DOE-supported field test under consideration that has been discussed previously. The analysis of the results of the two studies that correspond to those in Subtask 2.2 (with which they proceed in tandem) is nearing completion, and related papers are in preparation. In these studies, LBNL staff explored the feasibility of monitoring hydrate dissociation during potential long-term production tests at two sites: a) the Unit D deposit at the Mount Elbert site and (b) the Unit C deposit at the site of the PBU-L106 well. The two papers in preparation are:

(6) Geophysical Monitoring of Gas Production From a Cold, Stratigraphically Bounded Hydrate Deposit at the Mount Elbert Site, North Slope, Alaska, by M. Kowalsky, S. Nakagawa, and G.J. Moridis, to be submitted for publication to an appropriate peer-reviewed journal.

(7) Design of a potential long-term test of gas production from a hydrate deposit at the PBU-L106 site in North Slope, Alaska: Feasibility of seismic monitoring, by M. Kowalsky, L. Chiaramonte, and G.J. Moridis, to be submitted for publication to an appropriate peer-reviewed journal.

A paper on the results of the study on the PBU-L106 site was presented at the 2009 Fall Meeting of the American Geophysical Union (14-18 December 2009). Due to the fact that changes in the hydrate accumulation are limited to the near-well region (less than 40 m after 2 years), we found that the sensitivity of VSP measurements (at least for the first configuration we tested) is only modest and less promising than for previously examined cases (see discussion of next paper). Currently we are evaluating additional

measurement types (e.g., cross-borehole measurements) and configurations to optimize monitoring potential.

The following paper on a related study evaluating the feasibility of using geophysical methods to monitor on gas production from hydrate deposits in the Gulf of Mexico has been accepted for publication, and is currently in press:

(8) Feasibility of Monitoring Gas Hydrate Production with Time-Lapse VSP, by M. Kowalsky, S. Nakagawa and G.J. Moridis, in press, *SPE Journal*.

This study represents the first time that a geophysical method, vertical seismic profiling (VSP) in particular, has been evaluated for tracking hydrate dissociation at the field scale. In this study we considered a hydrate accumulation in the Gulf of Mexico and found that synthetic VSP measurements are sensitive to changes occurring in the hydrate accumulation during production. For the case of an incoming P-wave source, the most reliable indicators of change in the hydrate-bearing layer (HBL) appear to be converted S-waves transmitted through the HBL and recorded below it, and reflected P-waves and converted S-waves recorded above the HBL. Our modeling approach allows for the coupled simulation of hydrate production and corresponding geophysical measurements, which can provide a means to design cost effective geophysical surveys for monitoring hydrate production and related geohazards.

Subtask 2.4: Support to other DOE national and international projects

This task was competed. The LBNL hydrate research team continued to provide support to the various DOE national and international projects, interacting with US scientists working for DOE-supported national laboratories and foreign scientists involved in DOE-related international activities. As part of this task, the LBNL team organized and hosted the US-Korea Gas Hydrate Workshop at the LBNL campus in Berkeley on April 27-29, 2009. The Workshop was attended by over 30 US and Korean scientists, and developed a pathway for the development of joint research programs in support of Korean activities focusing on gas production from marine hydrates in the Ulleung Basin in the Korean East Sea.

Task 3: Assessment of Resource Recoverability From Natural Hydrate Deposits

Subtask 3.1: Gas Production From Oceanic Hydrate Deposits

Work on this subtask is ahead of schedule. Several investigations that began the previous year were completed in this period, and the results are presented in the following papers:

(9) Evaluation of the Gas Production Potential of Marine Hydrate Deposits in the Ulleung Basin of the Korean East Sea, by G. Moridis, M. Reagan, S.-J. Kim, Y. Seol, and K.Zhang, in press, *SPE Reservoir Evaluation and Engineering* (doi: 10.2118/110859-PA).

This work assessed production strategies and production potential of Class 2 and 3 deposits in the Ulleung Basin. The Class 2 system was able to produce at average rates of

2 MMSCFD for 10 years, using a constant mass-rate with minimal formation of secondary hydrate. Lower initial hydrate saturation, higher initial temperature, higher permeability, and decreased well spacing all increased deposit productivity. The Class 3 system was able to produce at an average rate of 2.8 MMSCFD over 30 years, under constant-pressure production, despite the formation of moving secondary hydrate barriers. As see in previous studies, the constant-*P* production strategies allow such barriers to "self heal" during the production process. Higher initial temperature, higher permeability, and decreased well spacing all increased deposit productivity, while productivity increases due to lower initial hydrate saturation only exist at early times. For both Classes, we see a continuous and monotonic decline in water production at the well. In all cases, the presence of a confining overburden is critical.

(10) Toward Production From Gas Hydrates: Current Status, Assessment of Resources, and Simulation-Based Evaluation of Technology and Potential, by G.J. Moridis, T. S. Collett, R. Boswell, M. Kurihara, M.T. Reagan, C. Koh, and E.D. Sloan, in press, *SPE Reservoir Evaluation and Engineering,* **12**(5): 745-771, 2009 (October 2009 issue, SPE-114163-PA, doi: 10.2118/114163-PA).

This comprehensive review article examines the distribution of natural gas hydrate resources, reviews the state of the hydrate literature, summarizes the status of various international R&D efforts, and the scientific and technical challenges facing the commercialization of hydrates. It highlights the role of numerical simulation in assessing production potential, and identifies the a) features, conditions, and geology that define the most desirable targets, b) the methods required to maximize production, and c) the characteristics that are most undesireable.

A new study analyzing the production potential of three new hydrate deposits discovered in the Gulf of Mexico in 2009 is in progress, and preliminary scoping calculations are being conducted. The following paper has been accepted for presentation at the 2010 Offshore Technology Conference (to be held in May 2010), and is currently under review:

(i) Preliminary Evaluation of the Production Potential of Recently Discovered Hydrate Deposits in the Gulf of Mexico, by G. Moridis, M. Reagan, R. Boswell, T. Collett, K. Boyle and K. Zhang – to be submitted after the OTC presentation for publication in one of the journals of the Society of Petroleum Engineers.

Another area of study currently in progress aims to determine the production potential of oceanic hydrate deposits that are characterized by the absence of confining boundaries, low hydrate saturation, and low-permeability sediments. Using data corresponding to the Tigershark formation, LBNL staff have completed an analysis of production from such deposits, including an evaluation of new well designs and configurations. The results of this study are reported in the following paper that was presented to the 2009 TOUGH Symposium (Berkeley, California, September 14-16, 2009):

(11) Evaluation of the gas production potential of challenging oceanic hydrate deposits, by G.J. Moridis, M.T Reagan, K.L. Boyle and K. Zhang (submitted to *Transport in Porous Media* for review).

This paper analyzes the production potential of deposits hampered by low productivity due to a) the absence of confining boundaries, b) high thermodynamic stability, c) low temperatures, and d) low permeability. The use of concurrent heating and production from segments along a single wellbore does not appear to solve the problems of production from these deposits, nor does a system using two parallel horizontal wells. Decreasing bottomhole pressure can increase productivity, but only with a corresponding increase in water production.

Within the framework of the same study on challenging hydrates, using data provided by Chinese colleagues from their 2007 expedition in the South China Sea, LBNL staff are in the process of analyzing and evaluating alternative methods (including new well designs and configurations) that may yield gas at commercially viable rates. This effort requires very large 3D grids of fine discretization (about 300,000 gridblocks), and the results will first be reported in the following papers (under preparation):

(ii) Evaluation of Gas Production Potential from Marine Gas Hydrate Deposits in the Shenhu Area of the South China Sea: Depressurization and Thermal Stimulation Methods, by G. Li, G. Moridis, G.J. Moridis, K. Zhang, and X. Li, paper accepted for presentation at the 2010 Offshore Technology Conference (to be held in Houston in May 2010) to be submitted after the OTC presentation for publication in one of the journals of the Society of Petroleum Engineers.

(iii) Numerical Investigation of Gas Production Strategies for the Hydrate Deposits in the Shenhu Area, by Z. Su, G.J. Moridis, K. Zhang and N. Wu, paper accepted for presentation at the 2010 Offshore Technology Conference (to be held in Houston in May 2010) – to be submitted after the OTC presentation for publication in one of the journals of the Society of Petroleum Engineers.

(iv) Production Potential of Oceanic Hydrates in the South China Sea, by K. Zhang, G. Moridis and N. Wu, paper accepted for presentation at the 9th International Oil and Gas Conference and Exhibition in China (to be held in Beijing in June 2010) – to be submitted after its presentation for publication in one of the journals of the Society of Petroleum Engineers.

Subtask 3.2: Gas Production From Permafrost-Associated Hydrate Deposits

Work on this subtask is in progress and ahead of schedule. Several investigations that began the previous year continued, were completed, and the results are presented in the following papers:

(12) Estimating the Upper Limit of Gas Production From Class 2 Hydrate Accumulations in the Permafrost, by G. Moridis and M. Reagan. This publication has been accepted pending minor revisions by the *Journal of Petroleum Science and Engineering.* As per the reviewers/editors suggestions, it will be broken into two shorter papers to allow all results to be published within reasonable length limitations.

The work assesses production from Class 2 permafrost-associated hydrates using three vertical well designs. Production from beneath the hydrate zone, combined with wellbore heating, is found to be the most effective method, yielding an average of 5.1 MMSCFD over 10.5 years. Production was found to be sensitive to small reductions in initial hydrate saturation; increasing the mass production rate yielded increases in production without the penalty of increases in the water/gas ratio.

(13) The Use of Horizontal Wells in Gas Production From Hydrate Accumulations, by G.J. Moridis, M.T. Reagan, and K. Zhang, in review for publication in the *Journal of Petroleum Science and Engineering*

The most important conclusions of this study are that (a) horizontal wells appear to confer no incremental benefits over vertical wells when used for gas production from Class 1 deposits, but (b) they result in significantly improved performance (often by orders of magnitude) when employed in gas production from Class 2 and Class 3 hydrate deposits.

Investigations are in progress to determine the production potential of challenging hydrate deposits that are characterized by high stability, proximity to aquifers, and extremely low effective permeabilities (which preclude reasonable flow). Using data from several permafrost locations, LBNL staff are in the process of analyzing and evaluating various production strategies that will result in economically sustainable gas production rates, while minimizing water production. This effort requires very large 3D grids of fine discretization, and the results will first be reported in the following paper under preparation:

(14) Evaluation of gas production from challenging hydrate deposits in the permafrost, by G. Moridis, M. Reagan and K. Zhang – to be submitted for publication in *Transport in Porous Media*.

NOTE: Published papers associated with Task 3 can be found online at: *http://esdtools.lbl.gov/info/hydrate-publications/production/*

Task 4: Predictive Studies of the Geomechanical Behavior in Hydrate-Bearing Systems

Work on this task was completed on schedule. The current effort focuses on the analysis of the effect of hydrate dissociation on oceanic slope stability under three conditions: (a) increasing ocean floor temperatures because of warming marine waters, (b) thermal loading of hydrate-bearing sediments by heat losses of ascending conventional reservoir fluids through non-insulated wells, and (c) gas production from hydrate deposits, during which the mechanical integrity of the deposit is adversely affected as the media-cementing hydrates dissociate. The first results of this study are included in the following publication (in preparation):

(vi) ***Geomechanical Response of Sloping Oceanic Hydrate Deposits to Thermal Loading and Production Activities***, by J. Rutqvist, G.J. Moridis and L. Chiaramonte, accepted for presentation at the 2010 Offshore Technology Conference (to be held in Houston in May 2010) – to be submitted after the OTC presentation for publication in one of the journals of the Society of Petroleum Engineers.

An additional study incorporates the results and conclusions gleaned from the geomechanical stability analysis of hydrate deposits that undergo dissociation in the course production in the design of wells. The results of this study are included in the following publication (in preparation):

(vii) ***Well Design Requirements For Deepwater And Arctic Onshore Gas Hydrate Production Wells***, by S. Hancock, G. Moridis, S. Wilson and A. Robertson, accepted for presentation at the 2010 Offshore Technology Conference (to be held in Houston in May 2010) – to be submitted after the OTC presentation for publication in one of the journals of the Society of Petroleum Engineers.

The following study on the geomechanical system response and stability analysis during production from oceanic hydrates (focusing on the Tigershark deposit) was completed and published in this period:

(15) ***Numerical studies on the geomechanical stability of hydrate-bearing sediments***, by J. Rutqvist and G. Moridis, *SPE Journal,* **14**(2): 267-282, 2009 (June 2009 issue, doi:10.2118/126129-PA).

These simulation results indicate that the stability of HBS in the vicinity of warm pipes may be affected significantly. Gas production from oceanic deposits may also affect the geomechanical stability of HBS under the conditions that are deemed desirable for production, and can lead to substantial subsidence. Conversely, the increased pressure caused by the weight of structures on the ocean floor increases the stability of underlying hydrates.

The following study on the comparative geomechanical behavior of two permafrost-associated deposits (the Mallik deposit in Northwest Territories, Canada, and the Unit C deposit at the Mount Elbert site, Alaska) was also completed and published in this period:

(16) ***Geomechanical response of permafrost-associated hydrate deposits to depressurization-induced gas production***, by J. Rutqvist, G.J. Moridis, T. Grover and T. Collett, *Journal of Petroleum Science and Engineering*, 67:1-12, 2009 (July 2009 issue, doi: 10.1016/j.petrol.2009.02.013).

The simulation results in this study show that general thermodynamic and geomechanical responses are similar for the two sites, but with substantially higher production and more intensive geomechanical responses at the deeper Mallik deposit. The depressurization-induced dissociation begins at the well bore and then spreads

laterally, mainly along the top of the HL. The depressurization results in an increased shear stress within the body of the receding hydrate and causes a vertical compaction of the reservoir. However, its effects are partially mitigated by the relatively stiff permafrost overburden, and compaction of the HL is limited to less than 0.4%. The increased shear stress may lead to shear failure in the hydrate-free zone bounded by the HL overburden and the downward-receding upper dissociation interface. This zone undergoes complete hydrate dissociation, and the cohesive strength of the sediment is low. We determined that the likelihood of shear failure depends on the initial stress state as well as on the geomechanical properties of the reservoir.

NOTE: Published papers associated with Task 3 can be found online at: *http://esdtools.lbl.gov/info/hydrate-publications/geomech/*

Task 5: Communications and Technology Transfer

Activities in this task were completed ahead of schedule. All the papers numbered with Arabic numerals that are discussed in this progress report have already been accepted or are to be published in peer-reviewed journals, and have already been presented, or will be presented, to scientific meetings; the papers numbered with Latin numerals are in the process of review for possible acceptance for presentation at future scientific meetings. As each paper completes the review process, a copy is posted on the LBNL publications server, under the location: *http://esdtools.lbl.gov/info/hydrate-publications.html*

G. Moridis has been invited to be the organizer of two sessions on gas production from hydrates during the 2010 Offshore Technology Session (to be held in Houston, Texas, in May 2010). Additionally, G. Moridis has been invited to join the Technical Program Committee of (a) the OTC Arctic Technology Conference (to be held in Houston in November 2009) and (b) the SPE 9th International Oil and Gas Conference and Exhibition in China (to be held in Beijing in June 2010), in both of which he will be a session chair in charge of unconventional resources and responsible for inclusion of representative studies of gas production from hydrates, in addition to being a keynote speaker presenting his DOE-supported work. G. Moridis is beginning his tour as a SPE Distinguished Lecturer (lecturing on hydrate-related subjects that are based on DOE-supported studies) in October 2009.

Additional General Publications

The following hydrate-related papers in which LBNL staff had significant contributions were published in this period:

(17) Preliminary report on the commercial viability of gas production from natural gas hydrates, by M.R. Walsh, S.H. Hancock, S.J. Wilson, S.L. Patil, G.J. Moridis, R. Boswell, T.S. Collett, C.A. Koh and E.D. Sloan, *Energy Economics*, **31**(5): 815-823, 2009 (September 2009 issue, 10.1016/j.eneco.2009.03.006).

(18) Occurrence of gas hydrate in Oligocene Frio sand: Alaminos Canyon Block 818: Northern Gulf of Mexico, by R.D. Boswell, D. Shelander, M. Lee, T. Latham, T.

Collett, G. Guerin, G. Moridis, M. Reagan and D. Goldberg, *Journal of Marine and Petroleum Geology*, **26**(8): 1499-1512, 2009 (September 2009 issue, doi:10.1016/j.marpetgeo.2009.03.005).